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The failures of the standard model of cosmology require a new paradigm

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Cosmological models that invoke warm or cold dark matter can not explain observed regularities in the properties of dwarf galaxies, their highly anisotropic spatial distributions, nor the correlation between observed mass discrepancies and acceleration. These problems with the standard model of cosmology have deep implications, in particular in combination with the observation that the data are excellently described by Modified Newtonian Dynamics (MOND). MOND is a classical dynamics theory which explains the mass discrepancies in galactic systems, and in the universe at large, without invoking ‘dark’ entities. MOND introduces a new universal constant of nature with the dimensions of acceleration, a_0 , such that the pre-MONDian dynamics is valid for accelerations $a \gg a_0$, and the deep MONDian regime is obtained for $a \ll a_0$, where space-time scale invariance is invoked. Remaining challenges for MOND are (i) explaining fully the observed mass discrepancies in galaxy clusters, and (ii) the development of a relativistic theory of MOND that will satisfactorily account for cosmology. The universal constant a_0 turns out to have an intriguing connection with cosmology: $\bar{a}_0 \equiv 2\pi a_0 \approx cH_0 \approx c^2(\Lambda/3)^{1/2}$. This may point to a deep connection between cosmology and internal dynamics of local systems.

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1. Introduction

Newton¹ formulated his dynamics subject to the observational constraints from the Solar system, while Einstein developed his general relativistic field equation² with the prerequisite that they reproduce Newton’s work in the classical, non-relativistic

limit. General relativity has successfully passed tests in the astronomically small-spatial-scale and strong acceleration limit (Solar system and smaller in length scale and stronger in acceleration scale). The presently favoured understanding of cosmological physics is based on assuming Einstein's field equation to hold on galactic and larger scales and for very small accelerations as are found in galactic systems (postulate 1). In addition, it is assumed that all matter emerged in the Big Bang (postulate 2). The first two postulates lead to an inhomogeneous and highly curved cosmological model which is in disagreement with the observed distribution of matter, unless inflation is additionally postulated to drive the universe to near flatness and homogeneity briefly after the Big Bang (postulate 3). The structures and their kinematics which arise from this postulate again do not match the observed ones unless cold or warm dark matter (DM) is postulated in addition to aid gravitational clumping on galactic scales (postulate 4). This DM must, as observations constrain, consist of non-relativistic particles which only interact significantly through gravitation.³ The so constructed model does not match the observed increase in the rate of expansion unless it is additionally postulated that dark energy drives an emerging new era of inflation (postulate 5). The resulting five-postulate construction with its many parameters determined using observational data⁴ is referred to as the concordance cosmological model which is the currently generally accepted cold or warm DM-based standard model of cosmology (SMoC).^{5,6}

The SMoC can be used to compute the distribution of matter on galactic scales because it is based on Newtonian dynamics which is a linear and thus, in principle, readily computable dynamics theory.^{5,7} The complex processes of the baryons (heating, cooling, star-formation, stellar and other feedback) are dealt with by employing parametrised laws, but few rigorous convincing predictions have come forth due to the tunability of the modelling, the lack of adopted constraints from observed star formation processes, and due to the haphazardness of the many mergers each DM halo experiences.⁸ The statistical distribution of sub-halos on the scales of many kpc around normal galaxies is among the rigorous predictions of the SMoC. The other rigorous prediction is that dwarf galaxies formed from tidal material expelled during galaxy encounters (see Sect. 2) cannot contain substantial amounts of DM.

The computations by many research groups have demonstrated that the SMoC has significant problems, the number of which has been increasing with improving computer power.⁹ While the greatest problems (see below) are usually not discussed by DM advocates even when they do discuss problems for the SMoC, e.g. in Ref(5), it is held by most dark-matter advocates that virtually all problems mentioned by the respective authors can be solved once modelling the baryonic processes is improved with larger resolution.⁷ Thus, for example, one of the failures, the missing satellite problem,^{10,11} is deemed to have been solved by now:¹² according to the SMoC each DM halo ought to contain a large number of satellite DM halos which are the phase-space substructures that merge during the hierarchical formation of larger structures.¹³ Milky Way and Andromeda class galaxies ought to have many hundreds of satellite galaxies, each of which are immersed in their own DM halos.

The observed small number of satellites (currently 24 are known for the Milky Way and a slightly larger number is known for Andromeda) is then a result of the complex and tunable baryonic processes cleaning out baryons from the vast majority of satellite DM halos. Some of the problems of the SMOc have been used to investigate possible model extensions, for example by invoking new dark forces between the DM particles which affect structure growth on sub-kpc scales.¹⁴ These additional postulates do not significantly affect the distribution of sub-halos on scales of many kpc, as this is given by the hierarchical infall of DM into larger structures.

The SMOc has been stated to be in agreement with the large-scale distribution of matter (although the problems on the local 100 Mpc and 16 Mpc scales undermine this statement, Sec. 4) and with the cosmic microwave background (CMB) fluctuations.⁵ But it can only remain as a valid description of the real universe if every one of the postulates individually pass observational tests. In order to certify the validity of the SMOc and its dark-sector variants *robustly* against the observational data, tests must be developed which are insensitive to the details of baryonic physics. Various such tests have recently been devised,¹⁵ and here the two most important ones (Sec. 2, Sec. 3) with consistency checks (Sec. 4) are discussed. The observed correlation of kinematical properties of galaxies over several orders of magnitude in acceleration (Sec. 5) convincingly demonstrates that a gravitational theory which differs from Newton's is valid. The Modified Newtonian Dynamics (MOND) theory¹⁶ is in excellent agreement with these data and provides an apparently correct description of dynamics on galaxy scales (Sec 6).

2. The dual dwarf galaxy theorem

In any realistic cosmological theory two types of galaxies emerge. Primordial ('type A') galaxies form directly after the Big Bang from gravitational instabilities in the cooling baryonic matter. Tidal dwarf galaxies ('type B') form from interacting, rotationally-supported type A galaxies: from tidal arms, which fragment and form dwarf galaxies as well as star clusters. This is evident in many observations of interacting galaxies^{17–20} and in all high-resolution simulations of interacting galaxies.^{19, 21, 22}

Indeed, high-resolution simulations in the SMOc show that type A and type B dwarfs have different dynamical and morphological properties (see points (i) and (ii) below). This comes about because the formation of type A dwarfs is dominated by the collapse and mergers of dwarf DM halos in which the end products retain much of the DM. In the SMOc, a large number of these sub-halos orbit as bound type A sub-structures in the more massive host halos, many more than are observed: The missing satellite problem therewith emerges (Sec. 1). Type B dwarfs, on the other hand, cannot capture significant amounts of DM because they form from the 'cold' parts of (disc) galaxies, which exclude the DM. In the SMOc so many tidal dwarf galaxies are generated that to account for these, statistically, most of the observed

dwarf elliptical (dE) galaxies would have to be type B dwarfs.²³

The SMOc thus predicts that two types of galaxies ought to be abundant that have different dynamics: one showing DM, the other not. But in fact of observation, rotating late-type dwarf galaxies as well as faint dwarf-spheroidal galaxies show evidence for DM. A tidal dwarf galaxy which is observed to have a DM component does not immediately disprove the SMOc. DM may appear to be present in a tidal dwarf galaxy if it is wrongly assumed to be in dynamical equilibrium when, in fact, it is not, as it is being perturbed by a time varying tidal field from the host galaxy.^{24,25} And, a young tidal dwarf galaxy may be accreting gas and may thus not be in rotational equilibrium feigning a DM content.

All type A galaxies which are rotationally supported are known to precisely lie on the Baryonic-Tully-Fisher Relation (BTFR)⁴ which therefore must be defined by the DM halo if the SMOc is true. The physics responsible for the precise conspiracy of the putative DM halo and galaxy luminosity to produce the BTFR over many orders of magnitude in galaxy luminosity however remains unknown. Tidal dwarf galaxies that show evidence for DM because they are out of equilibrium ought not to lie on the BTFR, because the tidal perturbation of, or gas accretion onto, the dwarf would not likely conspire to place a DM-free type B galaxy onto the BTFR of the type A dwarfs.

The prediction made by the SMOc that there are two distinct classes of dwarf galaxy (the 'dual dwarf galaxy' theorem) is falsified by observations, as follows:⁹

(i) By invoking the BTFR of rotationally supported galaxies:^{26,27} Type B dwarfs do not contain DM and therefore cannot lie on the same BTFR of type A galaxies in the SMOc. But observations show them to lie on the same BTFR as type A galaxies. The rotational velocities of the type A galaxies therefore cannot be given by a DM halo. Therewith, galactic DM halos cannot exist and one of the major pillars of the SMOc (postulate 4) breaks away such that the whole model is falsified.

(ii) By considering the radius-mass relation of pressure-supported dwarf galaxies: dE galaxies are thought to be of type A and thus to form in putative DM halos. The final structural parameters of dE galaxies and type B dwarfs therefore cannot agree. But observations show type B dwarfs to be indistinguishable from dE galaxies.²⁰ Thus, DM halos cannot play a role in dwarf galaxies, leading to the same conclusion as under (i) above.

3. Significant anisotropic phase-space distribution of satellite galaxies

The SMOc robustly predicts the primordial DM dominated (type A) satellite galaxies in a major halo to be distributed spheroidally around the host galaxy. The infall of satellite galaxies from filaments leads only to mild anisotropies.²⁸

The Milky Way galaxy, being part of the universe, must conform to these predictions. Instead the Galactic satellite system forms a vast polar structure (VPOS) which is a disk-like distribution²⁹ about 40 kpc thick and 400 kpc in diameter con-

taining all known satellite galaxies as well as all young halo globular clusters and about half of all known stellar and gas streams.³⁰ The proper motion measurements of 10 satellite galaxies show 9 of the satellites to be orbiting within the VPOS (one satellite is on a counter-rotating orbit in comparison to the 8 others). One satellite, Sagittarius, orbits perpendicularly to the VPOS and to the MW. To have nine of ten type A (DM sub-halo) satellites with measured proper motions orbiting within the VPOS is ruled out with very high confidence.³¹

Andromeda also has an anisotropic satellite system,^{32,33} and a few other galaxies are known which have satellite galaxies arranged in highly correlated phase-space structures.⁹ The prediction of the SMoC is therewith ruled out conclusively because the Milky Way is not unique in this property.^{9,15,34}

4. Consistency tests

The falsification⁹ of the SMoC with the above argument has deep implications. Can this argument be erroneous? A number of auxiliary tests have been developed,¹⁵ which the SMoC again does not pass. A visualisation of the results of the comparison between many predictions and observational data is presented in the theory confidence graph.⁹ If each of the 22 listed failures were to be associated with a loss of confidence of (only) 50 per cent that the SMoC accounts for a particular property of the real universe, then according to the confidence graph, the overall probability that the SMoC is a valid theory of the universe would be 0.5 raised to the power of 22, corresponding to a confidence of 2.3×10^{-5} per cent.

Three examples of such problems are the cusp/core problem, the downsizing and the missing-bright-satellites problem. These are usually acknowledged as problems, but claimed to be (probably) solvable.^{5,7,12,35,36} The real problems for which no solution can be identified are usually not mentioned in the DM literature: (a) The dual dwarf galaxy theorem and satellite anisotropy failures discussed above are catastrophic for the SMoC. (b) In the Local Volume with radius of 8 Mpc around the Sun, the matter distribution in the Local Void and near the edges of the filaments containing galaxies is incompatible with the expectations from the SMoC.³⁷ (c) The 50 Mpc radius region around us is missing DM by a factor of 3–4 while the fluctuations in the density must not be larger than about 10 per cent on these scales if the SMoC were true.³⁸ (d) Disk galaxies of similar mass are observed to show too little scatter in their properties,³⁹ which implies that galaxies obey laws that do not emerge in the SMoC.

5. The mass-discrepancy-acceleration correlation: towards galaxy laws

The rotation velocity, $V(r)$, measured at a radius r in a disk galaxy can be compared to the rotation velocity, $V_b(r)$, that one would expect due to only the observed baryonic matter. A plot of V^2/V_b^2 , which is the mass discrepancy at r , in a given galaxy as a function of r , gives the putative DM profile of the galaxy. As pointed out by

McGaugh,⁴⁰ combining many such measurements for many galaxies yields a mass-discrepancy vs r plot with no correlation. However, plotting the mass-discrepancy in dependence of the baryonic-Newtonian acceleration, $g_N = V_b^2/r$, yields a tight correlation (Fig. 1). The mass-discrepancy–acceleration correlation deviates from the Newtonian value below an acceleration of $a_0 \approx 1.2 \times 10^{-10} \text{ m/s}^2 = 3.8 \text{ pc/Myr}^2$ which is about five orders of magnitude smaller than the acceleration of Neptune in the Solar system.

No known physics of the DM particles can account for the observed mass-discrepancy–acceleration correlation. But this relation is convincing evidence for gravitational dynamics becoming non-Newtonian at accelerations $a < a_0$. This and many other correlations were *predicted* 30 years ago by Milgrom¹⁶ who introduced a new constant of nature, a_0 at the foundation of a new paradigm dubbed ‘Modified Newtonian Dynamics’ (MOND). In this paradigm Newtonian dynamics and general relativity are modified, so that galaxy dynamics is explained without the need for dark matter. Since its formulation in 1983¹⁶ MOND has passed all observational tests from $10^6 M_\odot$ dwarf disk galaxies⁴ to massive elliptical galaxy⁴¹ scales, with some tension remaining on the globular- and galaxy-cluster scales.⁹ These are, however, not major.^{42,43}

6. The MOND paradigm

While MOND has developed significantly in its particulars (such as formulations of various underlying theories), its basic non-relativistic (NR) tenets, from which follow all its major predictions, remain the same as originally proposed. These tenets, put in a somewhat improved form, are: (1) A new constant, a_0 , with the dimensions of acceleration is introduced into dynamics. (2) A MOND theory must tend to standard dynamics in the limit $a_0 \rightarrow 0$ (in other words, when the theory is applied to a system where all the quantities of dimensions of acceleration, a , are much larger than a_0). (3) In the opposite limit, $a_0 \rightarrow \infty$ (namely, when all $a \ll a_0$ in which case we also have to take $G \rightarrow 0$ so that Ga_0 remains fixed) the theory is postulated to become space-time scale invariant,⁴⁴ namely, invariant under $(t, \mathbf{r}) \rightarrow \lambda(t, \mathbf{r})$.

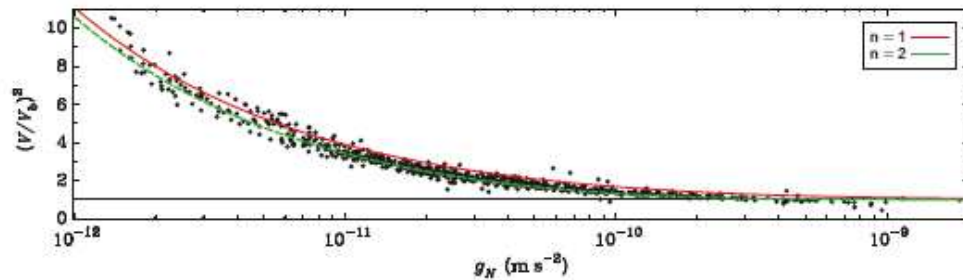


Fig. 1. The mass-discrepancy–acceleration correlation^{4,40} for disk galaxies. The red/solid and green/dashed curves are two different forms of the MONDian transition function as in fig. 11 in Kroupa.⁹ For the Solar system $g_N > 6 \times 10^{-5} \text{ m/s}^2$.

Conceptually, a_0 thus plays a role as a demarcation acceleration between the validity domain of the pre-MOND dynamics ($a \gg a_0$) and the MOND regime ($a \lesssim a_0$). In the former, a_0 disappears from physics, but in the latter domain a_0 appears with full impact on various phenomena. These roles are similar to those of Planck's constant in the classical-quantum context, and of the speed of light, c , in the classical-relativistic context. All these constants play the role of demarcations between the old and new physics. Also, taking them to the appropriate limit ($\hbar \rightarrow 0$ – the correspondence principle, and $c \rightarrow \infty$) takes one to the old, classical theory, in which these constants do not appear. Also, they all appear ubiquitously in the description of many, apparently unrelated phenomena^a in the new-physics regime. We shall see below how a_0 enters in many such phenomena and effects in low-acceleration galactic dynamics.

Newtonian gravitational accelerations, which scale as $g_N \propto MG/r^2$, transform under the above space-time scaling as $g_N \rightarrow \lambda^{-2}g_N$, while kinematic accelerations (\ddot{x}) transform as $g \rightarrow \lambda^{-1}g$. Newtonian dynamics, which equates the two, is thus not scale invariant. To have such a symmetry in the MOND limit we need g to scale like $g_N^{1/2}$; or, with the help of a_0 , $g \propto (a_0 g_N)^{1/2}$. This, more primitive, description of the MOND limit, is essentially the original formulation of MOND for test-particle motion.¹⁶ The formulation of the 3rd tenet in terms of scale invariance,⁴⁴ is, however, rather more elegant, precise, and general, and should be preferred.

Beyond the above basic tenets, one wishes to construct a full-fledged theory, and then extend it to the relativistic regime. Several relativistic and NR MOND theories are known. In the NR regime, we have the suitably chosen nonlinear extension of the Poisson equation,⁴⁵ and a quasilinear MOND formulation (QUMOND).⁴⁶ These are classified as ‘modified gravity’ (MG) theories as they modify the field equations of the gravitational field, but not the laws of motion. There are also ‘modified inertia’ (MI) formulations, which do the opposite. For the latter there isn't yet a full fledged theory, but, nonetheless, much can be said about their predictions of rotation curves.^{47,48} In the relativistic regime we can mention as examples, TeVeS,⁴⁹ and its predecessors, MOND adaptations of Einstein aether theories,⁵⁰ bimetric MOND (BIMOND),⁵¹ one based on a polarizable medium,⁵² and non-local, single metric formulations.⁵³ Much work has also been done over the years towards devising observational tests of MOND and on comparing MOND predictions with observations. Extensive recent reviews of these aspects of the MOND paradigm exist.^{4,54}

Quantum theory and relativity were not mere changes in form of the equations of classical dynamics. They each brought about totally new concepts to underlie dynamics. Likewise, there are reasons to presume that what we know about MOND today is only the tip of an iceberg.⁴⁴ One hint that this might be so is the ‘coincidence’¹⁶ $\bar{a}_0 \equiv 2\pi a_0 \approx c H_0 \approx c^2(\Lambda/3)^{1/2}$, where H_0 is the Hubble constant and Λ is the cosmological constant (CC). This, and some aspects of symmetry, may point to

^aFor example, in quantum theory: the black-body spectrum, the photoelectric effect, the hydrogen spectrum, quantum Hall effect, etc.

a deep connection between dynamics within local systems, such as galactic systems, and the state of the universe at large. This connection, if firmly established, could be the most far-reaching implication of MOND.^b

The MOND theories mentioned above depart from pre-MOND dynamics in that they introduce a_0 , add new degrees of freedom, and modify the underlying action, but they do not deeply depart in spirit from their predecessor. Perhaps one of them will turn out to be an effective theory that captures the essence of the future deeper MOND theory.^c

In addition, there are several ideas and suggestions for a ‘microscopic’ basis of MOND. One such class of suggestions⁵⁵ propounds that the MOND departure from Newtonian dynamics arises from the fact that we do not live in a globally Minkowski space time, but in one governed by a CC. The recent discovery of a CC-like entity that affects cosmology points to the possibility that the universe is entering an era where it will be increasingly dominated by the CC. Such an eventual universe, a de Sitter universe, is characterized by a radius $R_\Lambda \equiv (\Lambda/3)^{-1/2}$. This fact might show itself in local dynamics in the form of the acceleration constant⁵⁵ $\bar{a}_0 = a_\Lambda \equiv c^2/R_\Lambda$, as indeed appears in the above-mentioned ‘coincidence’^d. For example, in a de Sitter universe, the quantum vacuum is modified from the Minkowskian one in such a way that the Unruh radiation seen by an accelerated observer depends both on a_Λ and on the observer’s acceleration a (assumed constant) in a way that may point to a MOND inertia law.⁵⁵

There have been several recent proposals^{56,57} for obtaining MOND dynamics by adding the element of the de Sitter background⁵⁵ to the idea of entropic-origin-of-dynamics suggested by Verlinde.^{58–60} In the above schemes, the a_0 that appears in galactic-scale dynamics is indeed related to the cosmological constant as $a_0 \sim a_\Lambda$ ^e. In a different approach,⁶¹ also hinging on entropic gravity, a_0 emerges as the Fermi energy on an holographic screen.

In the MOND-through-a-polarizable-medium theory,⁵² in MOND adaptations of Einstein-aether theories,⁵⁰ and in BIMOND,⁵¹ the relation $a_0 \sim a_\Lambda$ appears differently: In these theories a length parameter appears in two places in the action, one that ends up defining the CC, the other defining a_0 . If one insists, for economy or naturalness, to use the same quantity in both roles, the above relation holds. However, there is no compelling mechanism for forcing this economy.

In light of the uncertainty in what the final space-time-matter theory will look like, it is reassuring that one can predict^{62,63} a number of general dynamics laws,

^bSuch a cosmological connection might imply that various aspects of the MOND-standard-dynamics interplay may depend on cosmic time.

^cThe appearance in all these theories of an interpolating function is an indication that they can only be effective theories.

^dThis appearance of Λ is different from the standard appearance of R_Λ in correcting the large distance behavior of (Newtonian) gravity introducing a linear, repulsive force.

^eNote that \sim is used as a similarity sign indicating that two numbers are of the same order of magnitude, while \approx means two numbers are similar within a factor of a few.

which compare excellently with observations^{4,54} and are based almost entirely on the basic tenets. These laws are important to recognize and understand for several reasons: (1) They constitute the core predictions of MOND, obeyed by all MOND theories, present and future, that embody the basic tenets. (2) They focus attention on well defined, easy-to-grasp predictions of MOND. (3) They involve only limited information about the systems (such as global attributes) and hence are easier to test on large samples. (4) They constitute a list of ‘things to show’ in the competing paradigm of Newtonian-dynamics-plus-DM. Succinctly formulated, these laws are:

- (1) Speeds along an orbit around any isolated mass, M , become asymptotically independent of the size-scale of the orbit. For circular orbits, $V(r \rightarrow \infty) \rightarrow V_\infty(M)$.
- (2) $V_\infty(M) = (M G a_0)^{1/4}$.
- (3) In disc galaxies transition from ‘baryon dominance’ to ‘DM dominance’ occurs around the radius where $V^2(r)/r = a_0$.
- (4) The acceleration attributed to ‘DM’ can never much exceed a_0 .
- (5) The central surface density of ‘dark halos’ is $\approx \Sigma_M \equiv a_0/2\pi G$.
- (6) Quasi-isothermal (baryonic) systems have mean surface densities $\bar{\Sigma} \lesssim \Sigma_M$.
- (7) Quasi-isothermal or deep-MOND systems have a velocity dispersion $\sigma \approx (M G a_0)^{1/4}$.
- (8) The external field in which a system is falling affects its intrinsic dynamics.
- (9) Disc galaxies behave as if they have both disc and spherical ‘DM’ components.
- (10) MOND endows self gravitating systems with an increased, but limited stability.

In addition to these laws, it is also reassuring that even the more elaborate prediction of rotation curves in MOND follows almost entirely from the basic premises alone.⁶³ The accuracy of MOND’s prediction of full rotation curves of disc galaxies is particularly impressive, as shown by the analysis of over a hundred galaxies.⁴ Recently, MOND has also passed an acute test in accounting for the dynamics of elliptical galaxies.⁴¹

7. MOND vs dark matter

We have seen that the SMoC faces many difficulties in accounting for various aspects of data on galaxies (Sec. 2 – 4). But perhaps the most cogent argument against the SMoC is that MOND works^{62, 64, 65} (e.g. Fig. 1). This is not because MOND is a competitor, but because the many tight regularities and correlations between baryon and ‘DM’ properties, predicted by MOND, and confirmed in the data, are quite contrary to what is expected in the DM paradigm. In the DM paradigm, a present-day system is the haphazard end result of a complex history that affects baryons and DM very differently. The observed tight correlations argue against this.³⁹

It is important to emphasize that in MOND, the dynamics of a self-gravitating system is strictly predicted once its baryon distribution is given. But in the SMoC it is not possible to predict the dynamics of an individual primordial (type A) galaxy

just from its observed baryons; at best one can try to match a DM halo from an infinite family that will fit the observed dynamics. For example, given the baryon distribution of a disc galaxy, the MOND rotation curve is a prediction, while the DM curve is but a fit with much freedom allowed. In short, unlike for MOND, the SMoC cannot predict the relations between baryons and DM in any individual system because these depend on the unknowable history of the system. In the rare case where the SMoC does make a prediction (tidal dwarfs, i.e. type B galaxies), because their formation histories are well understood, it fails.⁶⁶

Angus⁶⁷ and others have demonstrated that MOND-based cosmological models are able to account for many observations such as the CMB and the Bullet cluster.

8. MOND and the dwarfs

In MOND the dual dwarf galaxy theorem predicts no systematic dynamical differences between primordial and tidal dwarf galaxies.^{26,27} For example, both rotational types A and B of dwarfs are predicted to fall on the same BTFR by MOND law 2 in Sect. 6, irrespective of their different formation paths. MOND is fully consistent with the existence of the VPOS around the Milky Way (Sec. 3) as being an ancient tidal structure in which the Galaxy's satellites formed as tidal dwarf galaxies and globular clusters. Tidal dwarf galaxies form naturally in MONDian galaxy interactions.^{68,69} The internal constitution of the Galaxy's dwarf-spheroidal satellites is well explained with MOND.^{70,71} No such consistent explanation can be achieved within the SMoC, because the high measured Newtonian mass-to-light ratios of the satellites are completely in contradiction with them being ancient tidal dwarf galaxies. This, however, is the only physically plausible explanation for the existence of the VPOS^{22,28} with counter-orbiting satellites.⁷²

9. Conclusions

The SMoC is based on five postulates (Sec. 1); it is reported as having appreciable success in describing the large scale structure and the CMB. More importantly, it has a long history of grave failures^f. The failures are not really surprising since the first and most fundamental postulate is equivalent to an extrapolation of the empirically established gravitational law by Newton and Einstein to scales many orders of magnitude below the Solar system acceleration scale. Instead, the data correlations unequivocally show dynamics at accelerations smaller than $a_0 \approx 1.2 \times 10^{-10} \text{m/s}^2$ to not be Einsteinian/Newtonian. Given the nature of the failures, dynamically significant cold or warm DM particles cannot be the explanation of the mass discrepancies. Observations strongly suggest that a complete theory of dynamics has to depart from standard dynamics below some critical acceleration that is a constant of nature. The extraordinary success of MOND in accounting for the observational

^fCompare to the standard model of particle physics which is known to be incomplete but since decades it has consistently been found to be in excellent agreement with the data.

data on galactic scales and its properties (Sec. 6–8) suggest that the expected underlying theory will contain a deep connection between the dynamics within local systems and the state of the universe at large. Understanding the deeper physical meaning of MOND remains a challenging aim. It involves the realistic likelihood that a major new insight into gravitation will emerge, which would have significant implications for our understanding of space, time and matter.

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